NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3132

FATIGUE TESTS AT STRESSES PRODUCING FAILURE IN 2 TO 10,000 CYCLES

24S-T3 AND 75S-T6 ALUMINUM-ALLOY SHEET SPECIMENS WITH A THEORETICAL STRESS-CONCENTRATION FACTOR OF 4.0 SUBJECTED TO COMPLETELY REVERSED AXIAL LOAD

By Herbert F. Hardrath and Walter Illg

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
January 1954

.P

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3132

FATIGUE TESTS AT STRESSES PRODUCING FAILURE IN 2 TO 10,000 CYCLES

24S-T3 AND 75S-T6 ALUMINUM-ALLOY SHEET SPECIMENS WITH A THEORETICAL STRESS-CONCENTRATION FACTOR OF 4.0 SUBJECTED TO COMPLETELY REVERSED AXIAL LOAD

By Herbert F. Hardrath and Walter Illg

SUMMARY

Notched specimens made of 24S-T3 and 75S-T6 aluminum-alloy sheet material, with theoretical stress-concentration factors equal to 4.0, were subjected to completely reversed axial loads. Failures occurred in less than 50 cycles at two-thirds of the static tensile strength and in as few as 2 cycles when the applied load was near the static strength of the specimen. The S-N curves were found to be concave upward for almost the complete range of fatigue lives; a reversal in curvature occurred at about 10 cycles of load. The fatigue strengths were equivalent for specimens made of each of the two materials and tested at stresses below 25 ksi; above that stress the 75S-T6 specimens had the greater fatigue strength. Compared on the basis of percent of ultimate tensile strength, the 24S-T3 specimens were stronger at all stress levels. Test techniques and special test apparatus are described.

INTRODUCTION

In the past, most investigations of fatigue behavior have been concerned with establishing the endurance limits (if any) or the fatigue lives at stresses well below the yield stress for the materials of parts in question. In some cases, however, design conditions make it necessary or desirable to know the expected life of parts subjected to somewhat higher stresses.

The available data on fatigue properties of steels tested at stresses producing failure in less than 30,000 cycles are summarized in reference 1. Only a few of the data are for tests which resulted in failure of the specimens in less than 1,000 cycles. All the latter tests were performed on unnotched specimens subjected to bending or axial load at a stress ratio R (ratio of minimum to maximum stress) of zero.

A special investigation on low-cycle fatigue of 24S-T aluminum alloy in direct stress is reported in reference 2. In these tests, failures were produced in 1 to 7 cycles by subjecting unnotched cylindrical specimens to completely reversed cycles of a given natural strain. The maximum true stress in each succeeding cycle increased until failure occurred; the maximum total increase in stress was about 12 percent.

Recent tests of sheet specimens at the Langley Laboratory of the National Advisory Committee for Aeronautics (ref. 3) revealed that, under axial loads with a stress ratio of zero and maximum stresses near the ultimate tensile strengths, failure occurred in approximately 10,000 cycles for unnotched specimens, 1,000 cycles for notched specimens with a theoretical stress-concentration factor K_T of 2.0, and 100 cycles for notched specimens with $K_T = 4.0$. The materials studied were 61S-T6 aluminum alloy, annealed 347 stainless steel, and heat-treated 403 stainless steel.

The present investigation was undertaken to extend the available data to commonly used aircraft structural materials. This report presents results of axial-load tests at $R = -1$ of 24S-T3 and 75S-T6 aluminum-alloy sheet specimens with $K_T = 4.0$. Most of the tests were at stress levels which caused failure in less than 10,000 cycles. A few tests were performed at lower stresses to compare the present data with those previously obtained at Battelle Memorial Institute (ref. 4).

SPECIMENS

The material used in these tests was obtained from a special stock of commercial 0.090-inch 24S-T3 and 75S-T6 aluminum-alloy sheet retained at the Langley Laboratory for fatigue test purposes. A detailed description of the materials and their mechanical properties may be found in reference 5. The sheet layout is shown in figure 1 of reference 6. Specimens used in this investigation were cut from pieces marked "S1" in the original layout. Ten specimens were cut from each such piece used. Each specimen was identified by the number on the piece from which it was cut plus a number from 1 to 10 to indicate its position within the piece.

The dimensions of the specimens used in this investigation are given in figure 1. The specimens were clamped in stacks and machined along their longitudinal edges. Then they were mounted individually on a combination turntable and cross-slide support and the notches were cut with a milling cutter rotated about an axis normal to the plane of the specimen. Milling tools having 0.100-inch diameters and helical cutting edges were used to cut the notches, which had a radius of 0.057 inch. The cutter speed was constant at 1,500 rpm for the 24S-T3 specimens and 1,000 rpm for the 75S-T6 specimens.

The surfaces of all specimens were left unpolished, except that burrs at the notches were removed with fine crocus cloth. The cloth was moved with light finger pressure in a longitudinal direction along the plane surfaces of the specimens at the bases of the notches.

EQUIPMENT

Two types of fatigue testing equipment were used in this series of tests. All tests which were expected to result in failure after more than 10,000 cycles were performed in subresonant fatigue testing machines (ref. 5) operating at 1,800 cpm. All other tests were performed in a double-acting hydraulic jack with a capacity of 120,000 pounds, which was modified for this purpose.

A photograph of the jack is presented as figure 2. The principal parts of this machine are: a constant-discharge pump, a rate-control valve, a four-way valve to direct the hydraulic pressure, a double-acting hydraulic ram, and a null-method air-operated weighing system. The machine operates in a manner similar to that of other hydraulic testing machines. The modifications consisted of the addition of an electric weighing system and an air servo for operating the four-way valve. Contacts on the electric load indicator were adjusted to actuate the air servo whenever the load on the specimen reached the desired value. The hydraulic pressure was thus directed to the opposite side of the load piston to reverse the direction of load application. Special grips similar to those used in the subresonant machines were added to permit testing of sheet specimens.

TESTING PROCEDURE

For tests in which failures were expected to occur in 20 to 10,000 cycles the rate-control valve was opened to its maximum opening and loads were automatically controlled by the mechanism described in the preceding section. The resulting load-time curve is illustrated in figure 3(a). The sudden unloading was due to the fact that the four-way valve permitted a sudden release of pressure on the loaded side of the piston. Since the rate control remained at a constant setting, the rate at which load was applied was approximately constant. The frequency of the load application thus decreased as the maximum load increased. The range of frequencies was 14 to 48 cpm. An electronic load-measuring device (ref. 5) was used to monitor the applied loads in automatically controlled tests. This procedure was considered necessary because certain time delays in the automatic control mechanism made precise adjustment of the limiting contacts on the electric weighing system difficult.

The loads were manually controlled during any test in which failure was expected to occur in less than 20 cycles. In these tests the rate-control valve was used to reduce the rate of load application near the extremities of the load cycle and the air servo was manually actuated when the load indicated by the air-operated load dial on the machine reached the desired value. The frequency of load application varied between 0.4 and 1.0 cpm. The resulting load-time curve is illustrated in figure 3(b). The sudden unloading was again due to the sudden release of pressure, and the curved parts of a cycle resulted from manipulation of the rate-control valve.

In all tests the loads were measured with a maximum error of approximately ±1 percent. The maximum error in load application occurred during the first few cycles of the automatically controlled tests while final adjustments were being made. These errors rarely exceeded 5 percent.

Guides similar to those used in previous tests (ref. 5) were used to prevent buckling of the specimens. A low-voltage current was passed through the specimen to operate a relay which stopped the pump when the specimen failed.

RESULTS AND DISCUSSION

The results of the tests on specimens made of 24S-T3 and 75S-T6 materials are presented in tables 1 and 2 and are plotted as S-N curves in figures 4 and 5, respectively. All stresses S_{max} are average stresses corresponding to the maximum load carried by the original net section. The tables and figures also include previously published data obtained on geometrically identical specimens made from the same lot of material and tested at Battelle Memorial Institute (ref. 4). The Battelle specimens were electropolished and were tested in Krouse axial-load machines at 1,100 cpm.

Probably of most direct interest to the aircraft structural designer is a discussion of the behavior of these specimens when tested at stresses in the vicinity of two-thirds of the design ultimate tensile strength (ref. 7). These stresses correspond to limit loads in a given part. The curves in figures 4 and 5 indicate that the 24S-T3 and 75S-T6 specimens tested at these stresses failed in 50 and 32 cycles, respectively.

The two S-N curves are concave upward for almost the complete range of fatigue lives. There appears to be a reversal of curvature at about 10 cycles of load. Specimens made of each material failed in as few as 2 or 3 cycles of load application when tested at stresses just below the static tensile strength. These results are in sharp contrast with most previously reported tests at high stresses on unnotched specimens, in which failures rarely occurred in less than 10^3 to 10^4 cycles.

The S-N curves presented in figures 4 and 5 have been replotted in figure 6 to permit comparison between results of tests on specimens made from the two materials. At any given stress below 25 ksi the curves for the two materials are identical within experimental scatter; above 25 ksi the 75S-T6 curve is somewhat higher by virtue of the higher ultimate tensile strength of this material. When fatigue lives are compared at given percentages of the ultimate tensile strength S_{ult} (fig. 7), the 24S-T3 material has the longer life at all stress levels.

The ultimate tensile strength of the notched specimens was within a few percent of the tensile strength of standard tensile test specimens (ref. 5); the 24S-T3 notched specimens failed at stresses below the minimum unnotched tensile strength and the 75S-T6 notched specimens failed at stresses higher than the maximum unnotched tensile strength. Similar results have been obtained previously, but there appears to be no method for predicting this behavior quantitatively.

Inspection of the data reveals good agreement between results obtained in Langley tests at 1,800 cpm and in Battelle tests at 1,100 cpm. The data from tests performed at lower frequencies in the 120,000-pound jack also appear to fall in line with data obtained in the tests at higher frequencies. Elimination of the electropolishing procedure in the preparation of specimens produced no apparent effect on fatigue results in the range in which comparisons could be made.

CONCLUDING REMARKS

The results indicate that repeated application of completely reversed high stresses in notched parts can produce failures in much smaller numbers of cycles than might be inferred from previously published data, most of which were for unnotched specimens. It should be remembered, however, that the specimens tested had notches with stress-concentration factors of 4.0, which is probably about as high as would knowingly be included in a design, and that the completely reversed loading condition produces failure in fewer cycles (for a given maximum stress) than other loading conditions. Further investigation will be required to obtain a more complete understanding of fatigue at high stresses for other more representative notches and other loading conditions.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 28, 1953.

REFERENCES

1. Weisman, M. H., and Kaplan, M. H.: The Fatigue Strength of Steel Through the Range From 1/2 to 30,000 Cycles of Stress. Proc. A.S.T.M., vol. 50, 1950, pp. 649-665.

2. Liu, S. I., Lynch, J. J., Ripling, E. J., and Sachs, G.: Low Cycle Fatigue of the Aluminum Alloy 24ST in Direct Stress. Tech. Pub. No. 2338, Am. Inst. Mining and Metallurgical Eng., Feb. 1948.

3. Hardrath, Herbert F., Landers, Charles B., and Utley, Elmer C., Jr.: Axial-Load Fatigue Tests on Notched and Unnotched Sheet Specimens of 61S-T6 Aluminum Alloy, Annealed 347 Stainless Steel, and Heat-Treated 403 Stainless Steel. NACA TN 3017, 1953.

4. Grover, H. J., Bishop, S. M., and Jackson, L. R.: Fatigue Strengths of Aircraft Materials. Axial-Load Fatigue Tests on Notched Sheet Specimens of 24S-T3 and 75S-T6 Aluminum Alloys and of SAE 4130 Steel With Stress-Concentration Factors of 2.0 and 4.0. NACA TN 2389, 1951.

5. Grover, H. J., Hyler, W. S., Kuhn, Paul, Landers, Charles B., and Howell, F. M.: Axial-Load Fatigue Properties of 24S-T and 75S-T Aluminum Alloy As Determined in Several Laboratories. NACA TN 2928, 1953.

6. Grover, H. J., Bishop, S. M., and Jackson, L. R.: Fatigue Strengths of Aircraft Materials. Axial-Load Fatigue Tests on Unnotched Sheet Specimens of 24S-T3 and 75S-T6 Aluminum Alloys and of SAE 4130 Steel. NACA TN 2324, 1951.

7. Anon.: Strength of Metal Aircraft Elements. ANC-5, Munitions Board Aircraft Committee, Dept. of Defense. Revised ed., June 1951.

TABLE 1.- AXIAL-LOAD FATIGUE TEST RESULTS FOR

24S-T3 ALUMINUM-ALLOY SHEET SPECIMENS

$[K_T = 4.0; R = -1]$

Specimen	Maximum stress, S_{max}, ksi	Fatigue life, N, cycles	Frequency, cpm	Remarks
A34 S1 2	68.6	-----------	-------	(a)
A30 S1 4	67.8	-----------	-------	(a)
A33 S1 8	66.0	2	0.5	(c)
A33 S1 6	66.0	3	.4	(c)
--------	65.4	-----------	-------	(a) & (b)
A30 S1 3	63.0	4	.7	(c)
A33 S1 1	63.0	5	.6	(c)
A30 S1 5	62.0	5	.5	(c)
A30 S1 2	62.0	5	1.0	(c)
A32 S1 9	60.0	9	.6	(c)
A32 S1 8	60.0	9	.8	(c)
A32 S1 6	60.0	12	1.0	(c)
A32 S1 2	55.0	12	1.0	(c)
A35 S1 8	55.0	13	1.0	(c)
A35 S1 5	46.2	34	24	(d)
A35 S1 7	44.0	37	19	(d)
A35 S1 5	39.4	70	19	(d)
A35 S1 3	39.4	77	19	(d)
A35 S1 9	34.5	131	24	(d)
A35 S1 10	34.5	174	25	(d)
A32 S1 5	34.5	176	14	(d)
A34 S1 7	34.5	181	20	(d)
A35 S1 4	29.6	422	26	(d)
A32 S1 10	29.6	432	25	(d)
A35 S1 2	27.6	711	30	(d)
A31 S1 10	24.5	1,390	40	(d)
A32 S1 1	24.5	1,580	35	(d)
A34 S1 1	22.5	2,586	39	(d)
A10 S3 B	22.5	3,200	1,100	(b)
A30 S1 1	17.5	9,514	48	(d)
A34 S1 3	17.5	10,000	1,800	(e)
A47 S3 B	17.5	10,000	1,100	(b)
A9 S3 B	12.5	53,400	1,100	(b)
A5 S3 B	10.0	121,500	1,100	(b)
A34 S1 4	10.0	498,000	1,800	(e)
A33 S1 3	8.0	354,000	1,800	(e)
A43 S3 B	8.0	944,400	1,100	(b)
A34 S3 B	7.5	1,256,700	1,100	(b)
A44 S3 B	7.0	6,309,100	1,100	(b)
A30 S1 7	7.0	7,725,000	1,800	(e)
A50 S3 B	5.0	>10,969,000	1,100	(b)

[a]Static tensile test.
[b]Battelle (ref. 4).
[c]Manually controlled.
[d]Automatically controlled.
[e]Subresonant machines.

TABLE 2.- AXIAL-LOAD FATIGUE TEST RESULTS FOR

75S-T6 ALUMINUM-ALLOY SHEET SPECIMENS

$[K_T = 4.0;\ R = -1]$

Specimen	Maximum stress, S_{max}, ksi	Fatigue life, N, cycles	Frequency, cpm	Remarks
B48 S1 8	87.6	-----------	-------	(a)
B50 S1 9	84.8	-----------	-------	(a)
B48 S1 9	83.5	3	0.4	(c)
B51 S1 10	83.5	3	.6	(c)
---------	82.5	-----------	-------	(a) & (b)
B46 S1 10	82.0	4	.5	(c)
B49 S1 10	82.0	5	.5	(c)
B48 S1 3	80.0	5	.5	(c)
B49 S1 3	80.0	5	.7	(c)
B48 S1 4	70.0	10	.7	(c)
B48 S1 10	70.0	10	.5	(c)
B48 S1 7	62.5	14	.6	(c)
B50 S1 8	62.5	15	.7	(c)
B48 S1 1	62.5	17	.7	(c)
B49 S1 2	55.0	24	14	(d)
B49 S1 9	55.0	24	14	(d)
B50 S1 5	47.5	50	1.0	(c)
B48 S1 6	47.5	51	17	(d)
B49 S1 4	40.0	85	19	(d)
B49 S1 7	40.0	115	19	(d)
B49 S1 5	32.5	329	23	(d)
B49 S1 8	32.5	365	22	(d)
B49 S1 1	25.0	2,228	28	(d)
B49 S1 6	25.0	2,371	28	(d)
B47 S1 7	24.5	1,588	32	(d)
B47 S1 5	20.0	5,261	48	(d)
B45 S3 B	20.0	5,300	1,100	(b)
B10 S3 B	16.25	17,800	1,100	(b)
B51 S1 2	15.0	30,000	1,800	(e)
B35 S3 B	12.5	70,000	1,100	(b)
B50 S1 6	10.0	274,000	1,800	(e)
B36 S3 B	9.25	339,200	1,100	(b)
B19 S3 B	8.5	969,200	1,100	(b)
B51 S1 9	8.0	10,232,000	1,800	(e)
B28 S3 B	7.5	1,652,300	1,100	(b)
B20 S3 B	7.5	4,722,000	1,100	(b)
B31 S3 B	5.5	>12,405,300	1,100	(b)
B29 S3 B	4.0	>10,247,800	1,100	(b)

[a]Static tensile test.
[b]Battelle (ref. 4).
[c]Manually controlled.
[d]Automatically controlled.
[e]Subresonant machines.

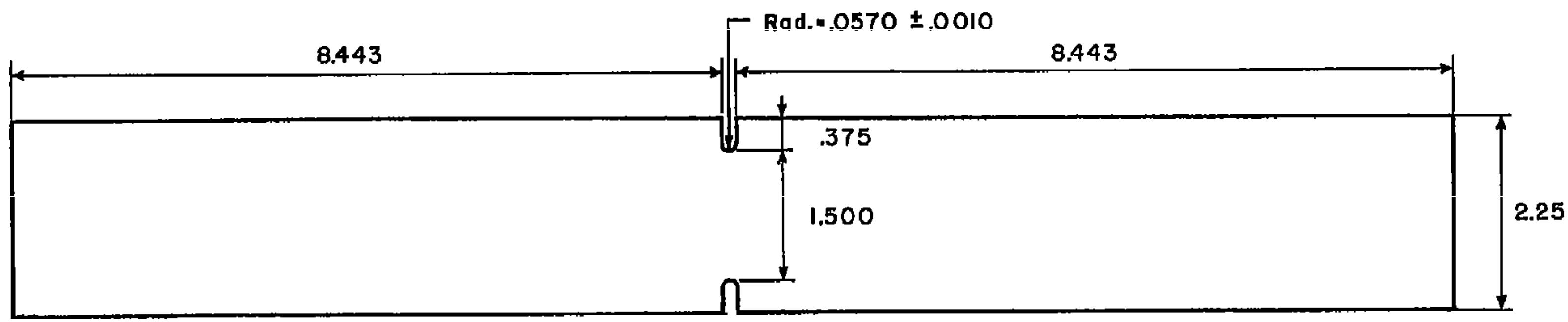
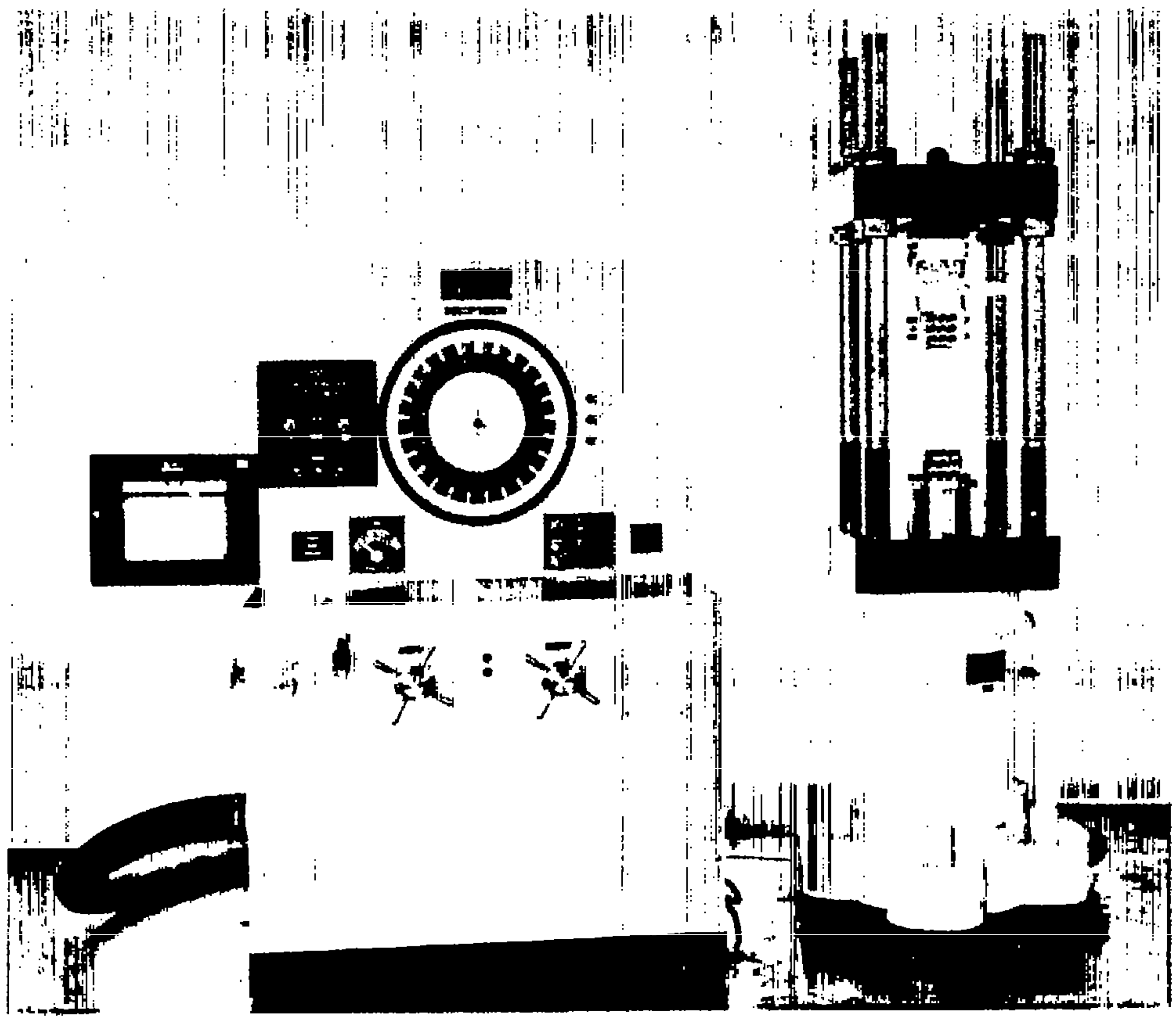
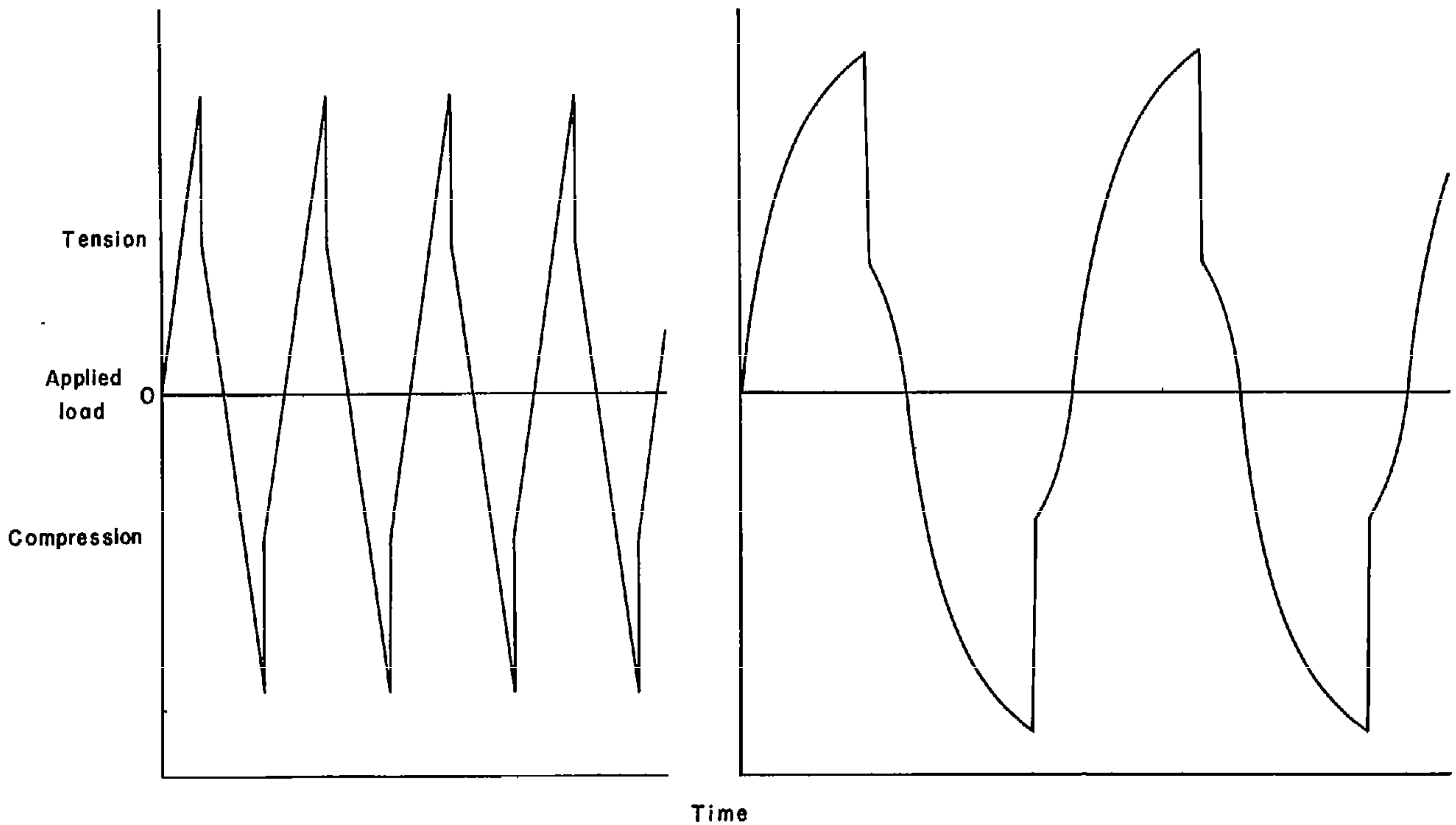


Figure 1.- Notched fatigue test specimen with $K_T = 4.0$.



L-80901.1

Figure 2.- Reversible hydraulic jack in test position.



(a) Automatically controlled. (b) Manually controlled.

Figure 3.- Typical load-time curves.

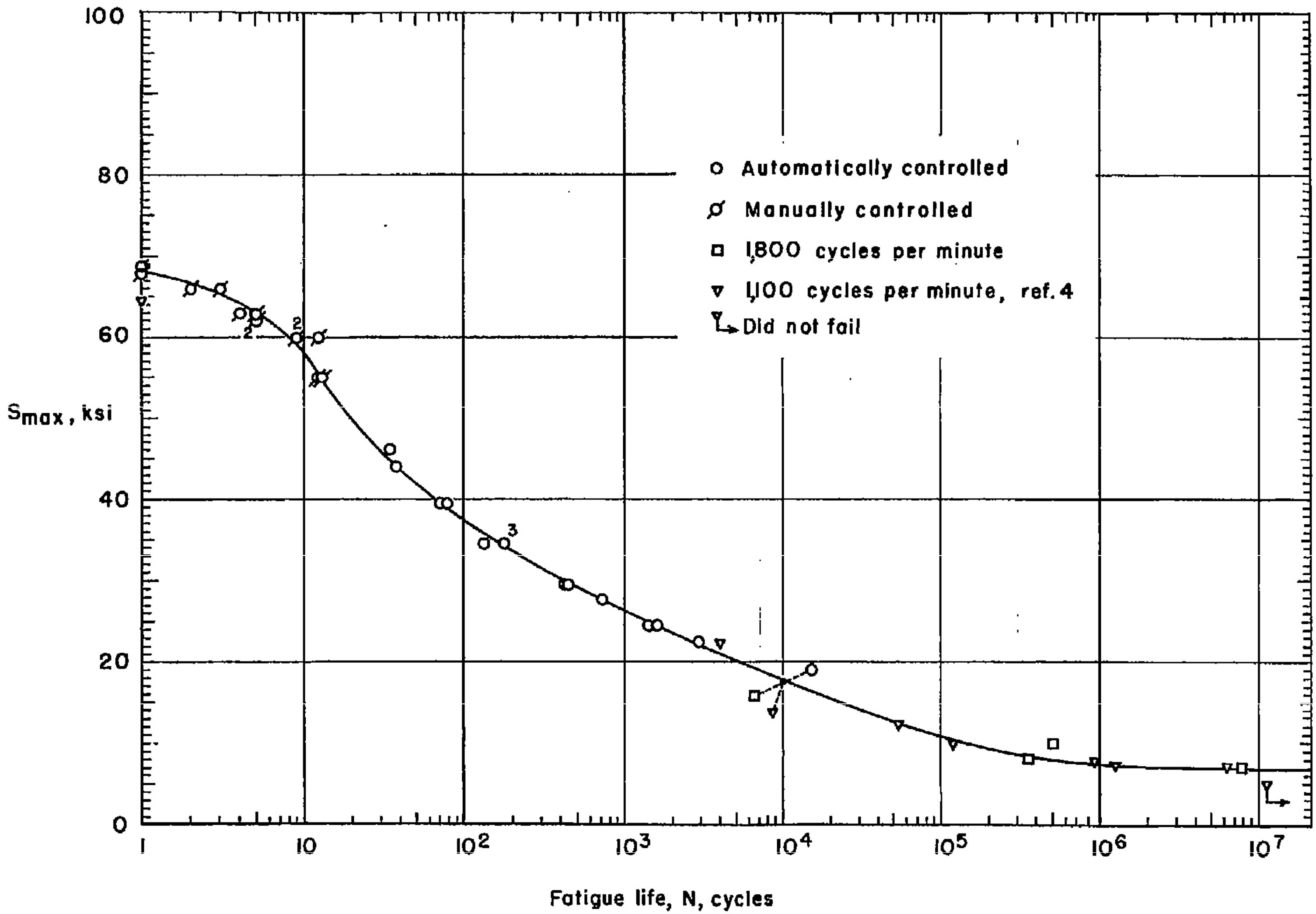


Figure 4.- Results of axial-load fatigue tests on notched 24S-T3 aluminum-alloy sheet specimens. $K_T = 4.0$; $R = -1$.

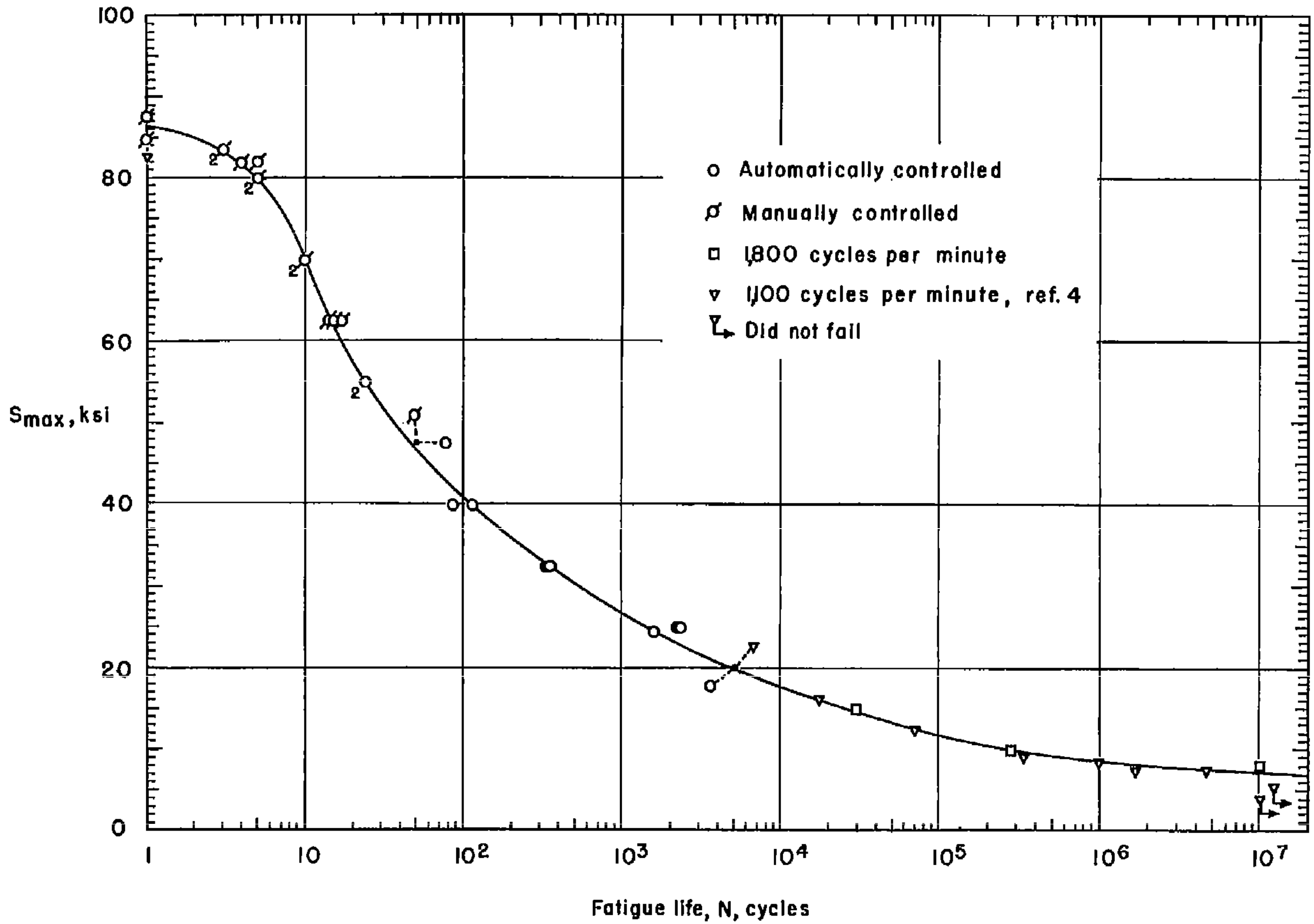


Figure 5.- Results of axial-load fatigue tests on notched 75S-T6 aluminum-alloy sheet specimens. $K_T = 4.0$; $R = -1$.

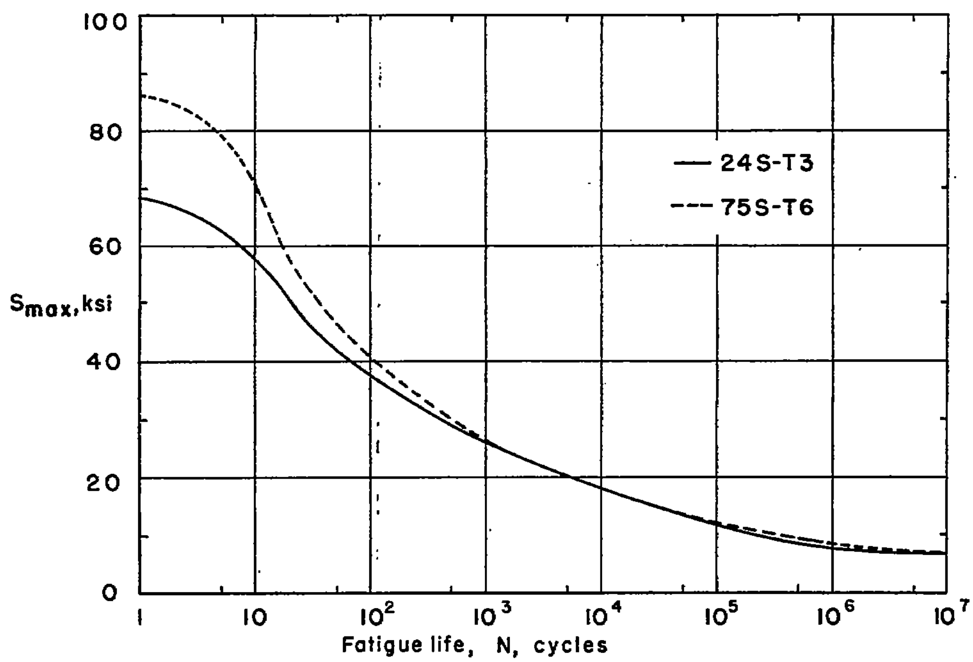


Figure 6.- Comparison of S-N curves for notched 24S-T3 and 75S-T6 aluminum-alloy sheet specimens. $K_T = 4.0$; $R = -1$.

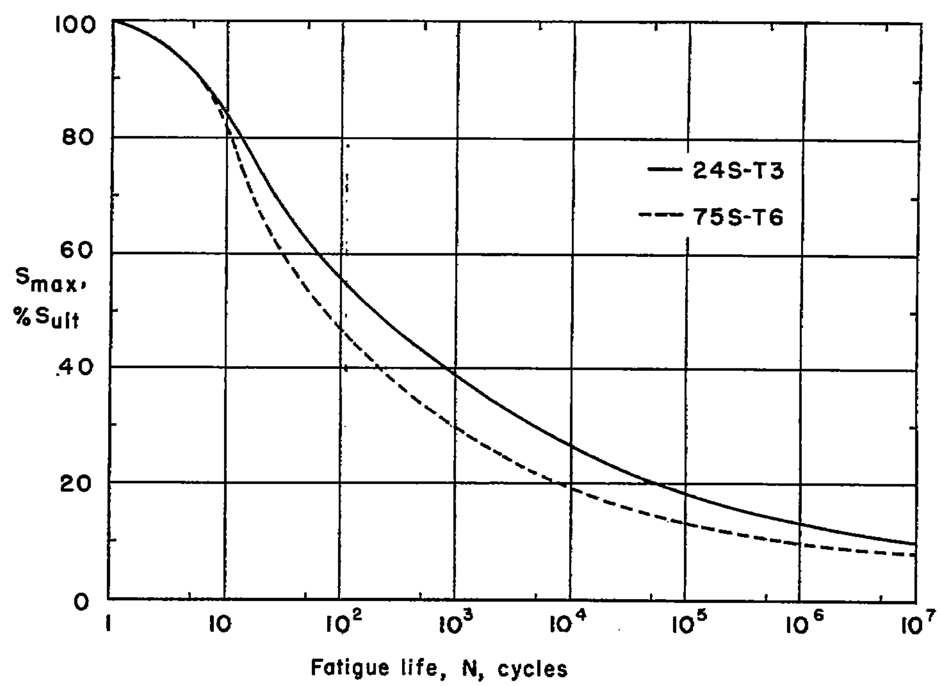


Figure 7.- Comparison of S-N curves for notched 24S-T3 and 75S-T6 aluminum-alloy sheet specimens. $K_T = 4.0$; $R = -1$. (Stresses are expressed as percentages of ultimate strength.)

NACA-Langley - 1-12-54 - 1000